Satellite Altimetry

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1. Project Summary

Sea level rise is potentially one of the more devastating consequences of global warming. As documented in a recent World Climate Research Programme workshop report[1], by 2010, 20 out of 30 of the world's meg-cities will be threatened by various degrees of inundation, enhanced erosion, and increased storm surge damage. The continuing rapid pace of U.S. coastal development is a particular concern, as Hurricane Katrina recently demonstrated in New Orleans.

The most compelling evidence of sea level rise comes from satellite radar altimeter observations. Figure 1 shows the altimeter-determined trend over the past 14 years compared with two historical estimates based on tide gauge observations. During the late 1800's – early 1900's the global mean level increased about 1 mm/yr, while during the second half of the 20th century the rate was 1.8 mm/yr. *The satellite altimeter observations indicate an even greater rate for the past decade, 3.1 mm/yr.* Measuring and explaining the cause of this apparent acceleration is a principle goal of the OCO Satellite Altimetry Program.

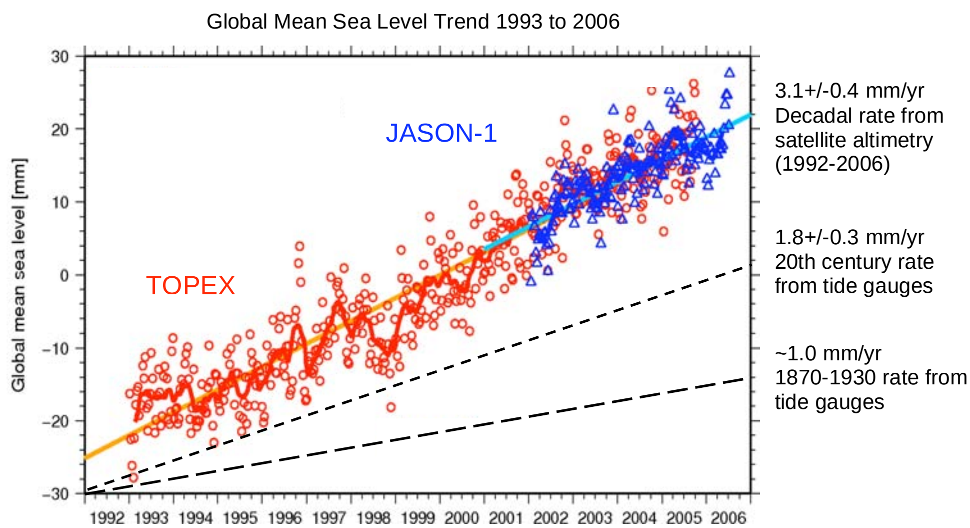

Figure 1. Global mean sea level trend from 1993 to 2006 based on TOPEX and JASON-1 altimeter observations. The trend over the past 14 years is roughly 2 times greater than the trend over the last half century and 3 times greater than the trend over the late 1800's – early 1900's. The latter two trends are based on tide gauge observations that only produce useful global estimates on intervals greater than 50 years, due to their limited geographical coverage.

Over the past several years we have developed several program elements that contribute toward this goal. They include:

- The design and maintenance of the NOAA Radar Altimeter Database System (RADS), a collection of all of the different satellite missions processed and inter-calibrated in a consistent manner, widely used by the research community.

- The production of high precision Geosat and Geosat-Follow-On (GFO) orbits. Through an agreement with the U.S. Navy, NOAA is responsible for producing and distributing a research grade GFO data set. Producing enhanced GFO orbits makes the data from this particular mission more useful for climate research purposes.
- The reconstruction of past sea level change from a combination of satellite altimeter and tide gauge measurements. Our understanding of sea level change over the past century is largely derived from tide gauge measurements that, by their nature, don't provide good spatial sampling. In contrast, the altimeter data set provides dense spatial, but short temporal (~15 years) sampling. This project investigates ways of combining these two complementary sets of observations to improve our estimates of past sea level change.
- Research into new methods of calibrating altimeter observations with tide gauge measurements. Although each altimeter is subjected to a rigorous pre-launch calibration procedure, 15 years of experience has taught us that each mission must be continuously calibrated for bias and drift errors with in-situ observations that only tide gauges can provide. This project investigates ways of improving our calibration procedures, with a particular emphasis on learning how to connect non-overlapping satellite missions for the estimation of sea level rise.
- The design and maintenance of a web-based, public source of altimeter/tide gauge calibration information for all current and past satellite missions.

The NOAA Laboratory for Satellite Altimetry (LSA) has long been involved in climate related studies of sea level, having participated in every satellite altimeter mission: Geos-3, Seasat, Geosat, ERS-1, Topex/Poseidon (T/P), ERS-2, Geosat Follow-On (GFO), Jason-1, and Envisat. Many of these have been research programs or operational demonstrations. However, since the mid-1990s it has been possible to produce quick-look, altimeter-generated analyses of sea surface height with sufficient accuracy and resolution to have operational utility. This capability is largely due to advanced satellite orbit determination techniques based on systems like the Global Positioning System. As a result, NOAA now incorporates satellite altimetry in a number of its operational products. For example, near-real time sea surface height analyses are assimilated into NCEP ocean models used to forecast El Niño, hurricane intensification, and coastal circulation. NOAA/LSA also maintains the Radar Altimeter Database System (RADS), used to analyze climate time scale phenomena, such as global sea level rise.

Because of the value of altimetry to NOAA and the U.S. Navy, a commitment has been made to fly altimeters operationally as part of the National Polar-Orbiting Operational Satellite System (NPOESS). Negotiations are presently underway between NOAA, Navy and NASA, to determine how to best meet this commitment. In the meantime, NOAA must continue to leverage its resources to take advantage of existing satellite altimeter missions, and prepare to assume responsibility for the Jason-2 ground system beginning in 2008.

LSA maintains connections with many agencies, institutions, and programs. LSA staff members serve on NASA's Ocean Surface Topography Science Team, the Envisat altimeter advisory group, and science teams for CryoSat, and IceSat. See http://ibis.grdl.noaa.gov/SAT/

This project contributes to the NOAA goals (1) Understand climate variability, and (2) Serve society's needs for weather and water information. It provides the satellite altimeter "research-to-operations" component of NOAA's Program Plan for Building a Sustained Ocean Observing System for Climate.

2. FY06 Accomplishments.

a.) Support of the NOAA Radar Altimeter Database System (RADS)

In order to monitor global sea level rise and other ocean climate phenomenon with satellite altimetry, it is essential that records from different satellite missions be processed and inter-calibrated in a consistent manner. The NOAA Radar Altimeter Database System (RADS), designed and maintained by Remko Scharroo serves this purpose, as well as providing a tool for studying important ocean "weather" problems such as hurricane intensity forecasting. Over the past year, this project has processed and incorporated into RADS the data from the three currently functioning altimeters (Jason-1, Envisat, GFO). Many significant improvements have also been made to the Geosat data set (1985-1988), including waveform re-tracking corrections and the incorporation of new, more precise orbits (Scharroo et al., 2006). The impact of all of these improvements on the estimation of sea level rise will be described in a talk to be presented at the upcoming Jason-1/OSTST meeting in March (Miller et. al, 2007). In addition to these climate related activities, Remko Scharroo has continued his investigation into the use of altimeter observations for hurricane intensity forecasting (Scharroo et. al, 2005, 2006).

b.) GFO and Geosat Precise Orbit Determination

The U.S. Navy's Geosat Follow-On (GFO) altimeter mission has been operational since 2000. During 2006, the LSA used OCO funds to support the computation of precise orbits (F. Lemoine, NASA/Goddard) and worked closely with the Navy, NASA, universities, and project contractors to prepare and distribute final, research-quality Geophysical Data Records (GDRs). Thus far, LSA has produced 5 years of GDRs and distributed the data to users on DVD http://ibis.grdl.noaa.gov/SAT/gfo/). GDR production and distribution will continue routinely for the life of the GFO mission. In addition to the research data sets, GFO is a source of near-real time sea surface height that is used by the Navy and NOAA for ocean and atmosphere operations. As an example, the National Hurricane Center uses all available altimetry to compute "hurricane heat potential" maps as an aid to forecasting storm intensification. GFO contributes significantly to this activity as evidenced by recent *EOS* articles on Katrina published by members of the LSA (Scharroo, et. al, 2005, 2006).

OCO funds were also used to pay for the computation of new, more precise orbits for the first 1.5 years of the original Geosat mission, using an improved gravity field based on GRACE measurements. The new orbits greatly have reduced the random errors from 10 to 5 cm rms.

c.) Reconstruction of Past Sea Level Change from a Combination of Satellite Altimeter and Tide Gauge Measurements

There are two primary datasets used for measuring sea level change. Tide gauge measurements provide estimates of sea level change over the past century, but with relatively poor spatial sampling. The tide gauge data have shown an average rate of sea level rise of ~1.8 mm/year over the last 70 years. Satellite altimeter measurements from the TOPEX/Poseidon (T/P) and Jason satellites provide precise global measurements of sea level since 1992, but the record is relatively short. T/P and Jason have observed a rise of global mean sea level of +3.2 ± 0.4 mm/year [*Nerem and Mitchum*, 2001a; *Nerem and Mitchum*, 2001b]. While this result is reasonably certain, critical questions still exist about the interpretation of this result in the context of long-term climate variations. Uncertainties in the interpretation of the tide gauge record make it difficult to determine if the altimeter-derived rate represents a significant acceleration of sea level rise relative to the historical record. The tide gauge record is over a century long, but suffers from poor spatial distribution and uneven coverage in time. The altimeter record is relatively short, but has excellent near-global coverage. Therefore, it is natural to consider trying to take advantage of the best features of each dataset to investigate long-term sea level change.

The primary purpose of this research is to develop improved techniques to reconstruct sea level change over the past century using a combination of tide gauge measurements and satellite altimeter data. There has been considerable interest recently in reconstructing past sea level change [*Chambers, et al.*, 2002; *Church and White*, 2006]. There are a variety of different ways to combine altimeter and tide gauge sea level measurements to reconstruct past sea level change. We have been examining the advantages and disadvantages of different reconstruction techniques in order to select an optimal approach. However, all of the techniques are limited by the relatively short altimeter sea level record. This is because the variance of the altimeter record does not span the variance of the sea level record over the last century. Fortunately, as the altimeter time series lengthens, the results from the reconstruction techniques will improve.

Over the past year, we conducted sea level reconstruction simulations using output from the Parallel Climate Model (PCM) to better understand the impact of the reconstruction techniques and their errors on recovered GMSL records,. Basically, we used the model output to simulate both a 13-year altimeter record (1987-2000) and a 100-year tide gauge record (1900-2000), and then tried to recover the PCM global mean sea level variations using EOFs of the alimeter record combined with the simulated tide gauge data. The reconstruction appears to perform quite well for periods longer than 10 years. However at shorter periods, there are significant errors in the reconstruction. The results of this study form the basis of a University of Colorado Masters thesis (Jakubs, 2006). A journal article version of this work is currently being prepared

d.) Altimeter/Tide Gauge Calibration Research

This project investigates ways of improving altimeter/tide gauge calibration procedures, with a particular emphasis on learning how to connect non-overlapping satellite missions for the estimation of sea level rise. This is an important goal for two reasons. Looking forward in time, there is a strong possibility of an altimeter gap emerging some time after 2013, due to funding problems and poor coordination between the various domestic and national programs. If there is a gap in the altimetric record of global mean sea level, it may be difficult to detect an acceleration in sea level rise due to uncorrected bias errors in the individual records. Looking backward in time, if a procedure could be developed for connecting non-overlapping missions it might be possible to lengthen the current time series by nearly 40% by combining the Geosat record with the TOPEX/Jason-1 records. A University of Maryland undergraduate student, Caroline Harbitz, was hired through CICCS to work with several members of the LSA on this problem over the summer of 2006 and also during the Winter 2007 semester break. The preliminary results from this study are very encouraging. Figure 2a shows a simultaneous fit to the unimproved (old orbits) Geosat, TOPEX, and Jason-1 data sets prepared by Remko Scharroo. Figure 2b shows the same fit using the improved Geosat data and a Geosat drift correction obtained from a comparison with tide gauge observations. The Geosat record has flipped from a steep downward trend a slight upward trend. Considerable work remains to be done to identify the cause of the Geosat drift and to reduce the bias errors. (Figure 2b does not use the bias correction derived from the altimeter/tide gauge comparison; it's still too poorly determined.) A paper describing work will be presented at the Jason-1/OSTM Science Working Team meeting in March (Miller, et al, 2007)..

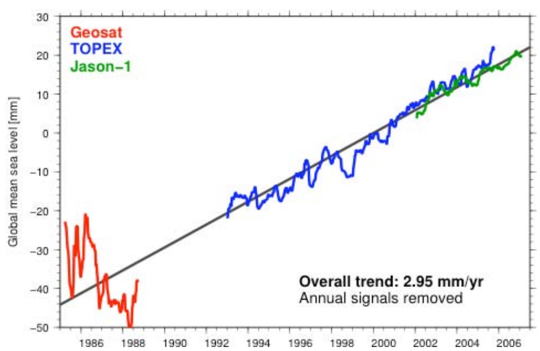

Figure 2a

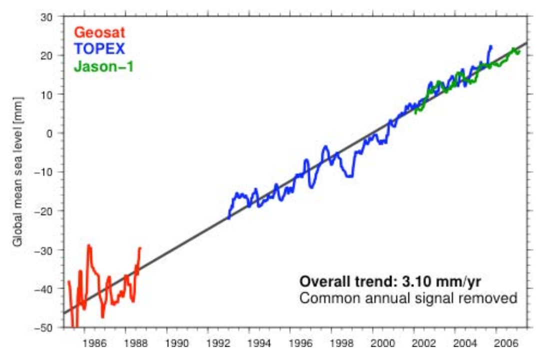

Figure 2b.

e.) Altimeter/Tide Gauge Calibration Web Site: Nancy Soreide, PMEL

The purpose of this project is to provide on a routine monthly basis a consistent set of tide gauge datasets (developed under other funding) for the calibration of current and historical satellite altimeter datasets. Although funds were received late in the fiscal year, progress has been made on this project. Funds have been put into contracts supporting the development effort. Dr. Gary Mitchum (University of South Florida) has reviewed existing successful websites providing similar data sets in order to determine the most effective and efficient way to provide data for this project. Two relevant websites included in the review include the OSCAR website (http://www.oscar.noaa.gov) and the Bering Sea Climate and Ecosystem website (http://www.beringclimate.noaa.gov). Out of these reviews, and after consultation with web experts at PMEL, the overall structure and layout of the website has been decided. It is possible some efficiencies can be achieved by code-sharing with the Bering Sea website. Preliminary design has been completed, but the implementation of the page may be delayed until the release of NOAA's new "One NOAA web page banner", which was approved in draft form by the

NOAA Executive Panel in mid-October 2006. Meanwhile, website navigation has been decided and we have a strategy for data presentation. If the release is delayed, we will need to revisit this decision, and perhaps proceed without the One NOAA web page banner.

3. Publications and Reports:

Jakub, T.D., "A Sensitivity and Error Analysis of a Sea Level Reconstruction Using Satellite Altimeter and Tide Gauge Data", Masters Thesis, University of Colorado, 2006.

Lillibridge, J.L., W.H.S. Smith, D. Sandwell, R. Scharroo, F. Lemoine, and N. Zelensky, "20 Years of Improvements to Geosat Altimetry", ESA 15 Years of Progress in Radar Altimetry Symposium, Venice, Italy, 2006.

Lillibridge, J.L., S. Calmant, "Geosat Follow-On Waveforms: Retracking for Hydrology Applications", ESA 15 Years of Progress in Radar Altimetry Symposium, Venice, Italy, 2006.

Miller, L., and B.C. Douglas, "Comparing Global Sea Level Rise Estimates from Satellite Altimetry and a Global Ocean Reanalysis: 1993-2001", ESA 15 Years of Progress In Radar Altimetry Symposium, Venice, Italy, 2006.

Miller, L., and B.C. Douglas, "On the Rate and Causes of 20th Century Sea Level Rise", *Phil. Trans. Royal Soc.*, **364**, 805-820, 2006.

Miller, L., R. Scharroo, J. Kuhn, C. Harbitz, "Extending the TOPEX/Jason global mean sea level time series with GEOSAT observations", Jason-1/OST Science Working Team Meeting, Hobart, Tasmania, 2007.

Scharroo, R., W.H.F. Smith, J.L. Lillibridge, "Satellite Altimetry and the Intensification of Hurricane Katrina", *EOS Trans. AGU*, **38**, (40), 366, 2005.

Scharroo, R., W.H.F. Smith, J.L. Lillibridge, "Reply to Comment on Satellite Altimetry and the Intensification of Hurricane Katrina", *EOS Trans. AGU*, **87**, (8),89, 2006.

Scharroo, R., L. Miller, A. Ridout, and S. Laxon, "Global and regional sea level change from multi-satellite altimeter data", ESA 15 Years of Progress in Radar Altimetry Symposium, Venice, Italy, 2006.